4D Tracking Detectors: Monolithic Fast Timing Silicon Detectors

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EIC Considerations

Luminosity
- up to 10^{34}
- expect ~1-2 interactions per event
  - Pileup should not be an issue, still need to identify primary vertex
- Bunch crossing ~10 ns
  - Fast readout or time stamp to identify bunch crossing for an event

Vertexing
- Hadron beam spot β = 5 cm

Particle identification
- time of flight
- dE/dx

Radiation damage
- Max 1×10^{15} 1 MeV n_{eq}/cm^2
  - Assuming ~1% of worst dose at HL-LHC
  - To be confirmed

Material Budget
- Keep as low as possible

Fast Timing Silicon Detectors

Proposal:

4D Tracking Detectors:
Monolithic Fast Timing Silicon Detectors

- Silicon already has small pixels (10-50 μm) for high spatial resolution
- Add timing resolution
  - better than bunch crossing
  - For vertex and track reconstruction
  - For particle ID
- MAPS may reduce cost and radiation length

Currently under investigation by Italian groups (INFN, Trento, Torino, …), London, and UC Santa Cruz

Never done before

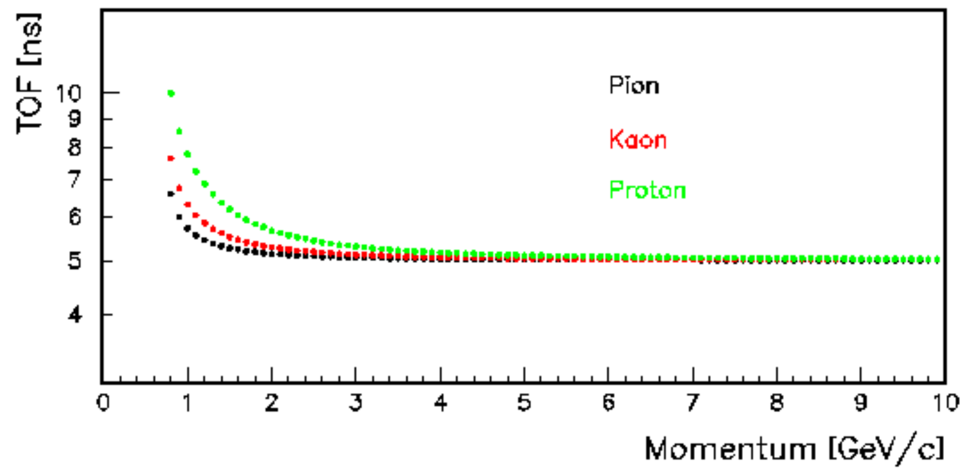
5D Detector: x, y, z, time, energy

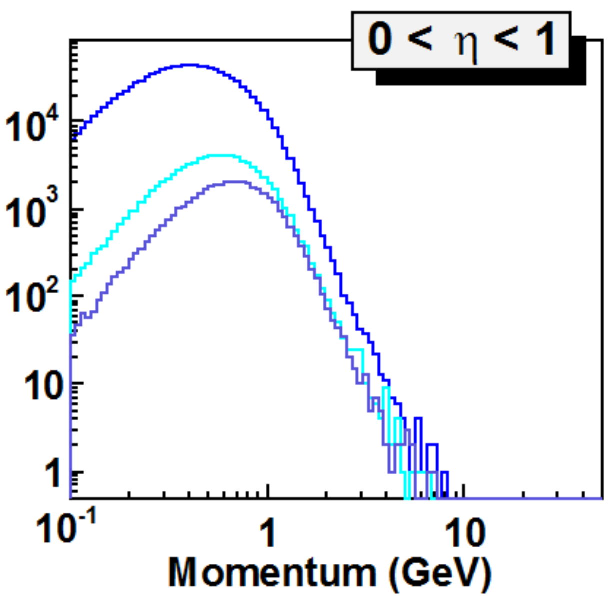
- Add as an option for an EM calorimeter

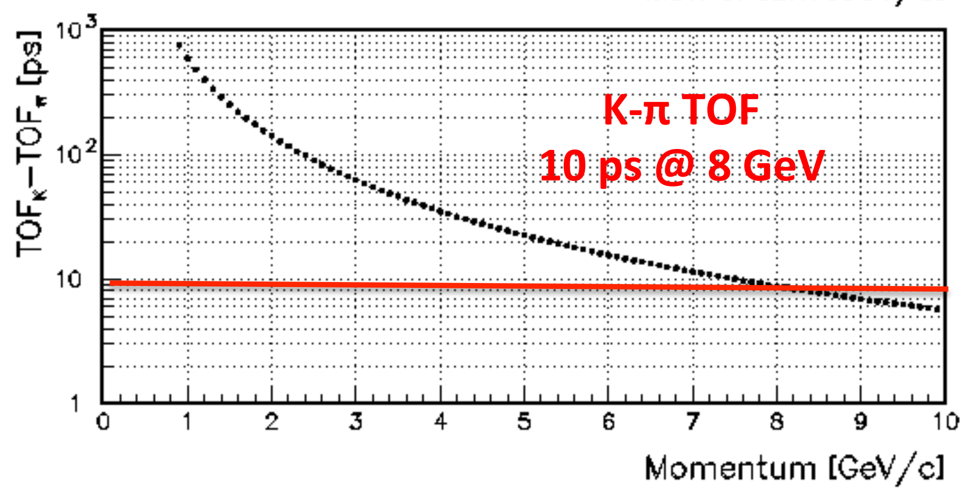
Timing for Particle ID

Particle ID:

- Expected energy range of charged particles is up to 10 GeV
- Using the time of flight, pion, kaon, and protons can be identified due to mass differences for a given momentum
- Kaon-pion separation requires resolutions on the order of 10 ps at 10 GeV

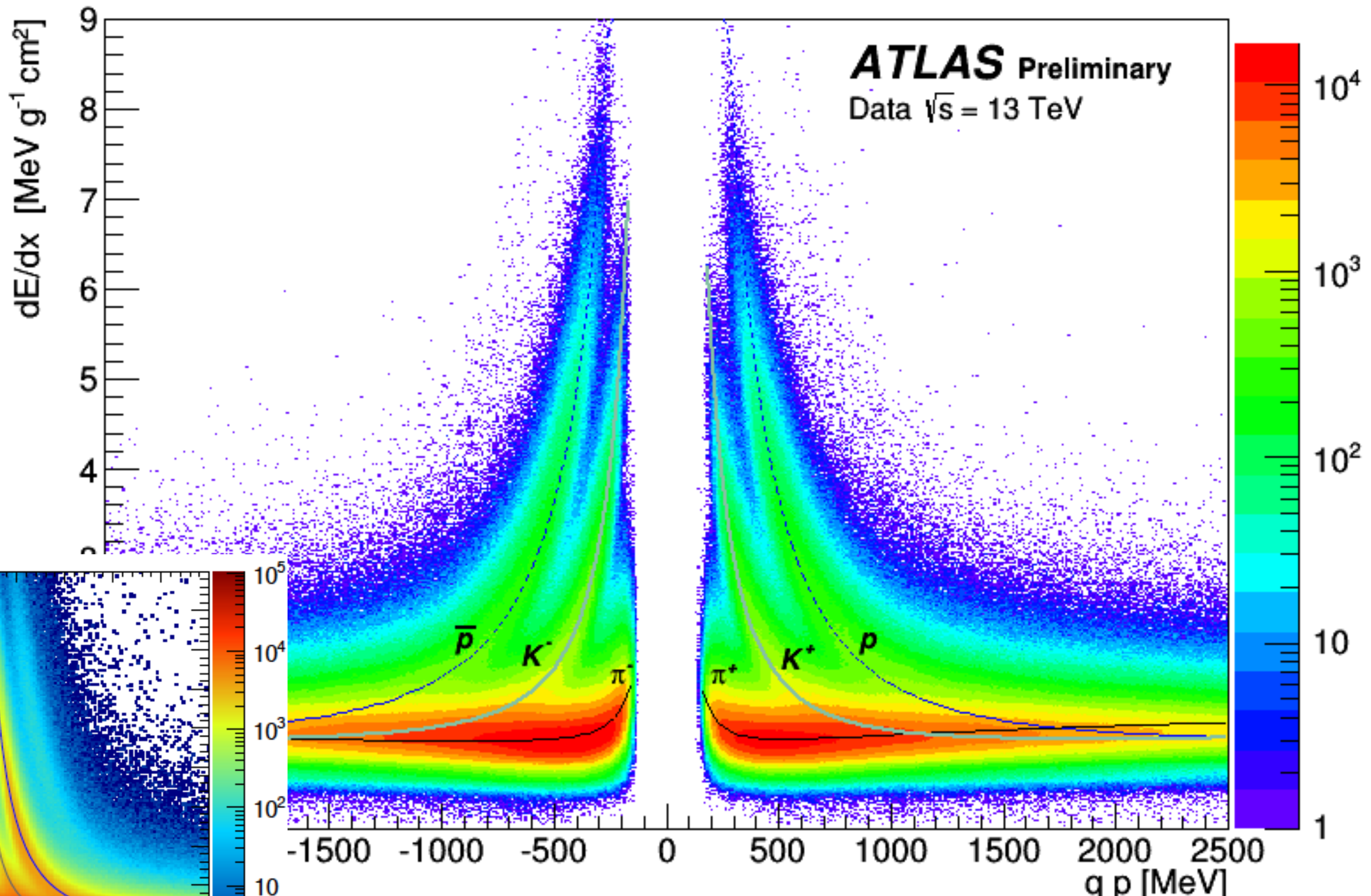


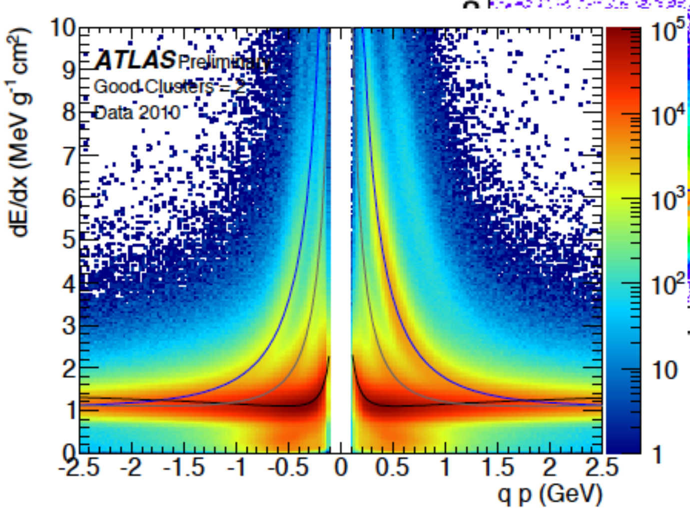




Timing for Particle ID

Particle ID:
Combined with dE/dx for enhanced particle ID





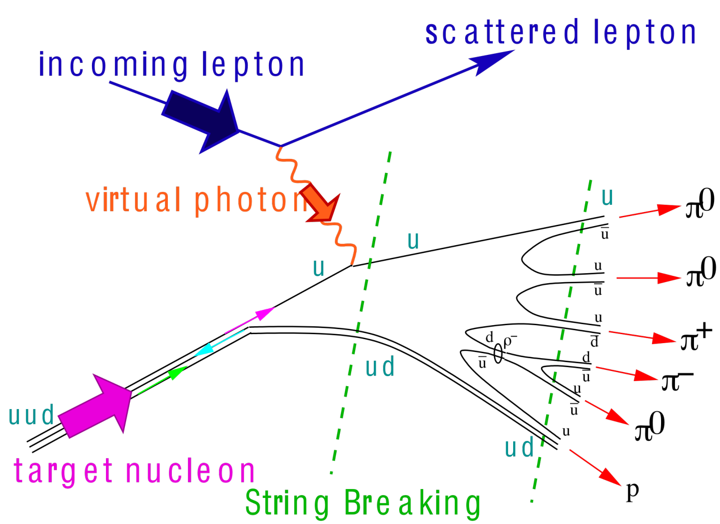
Timing for Track Reconstruction

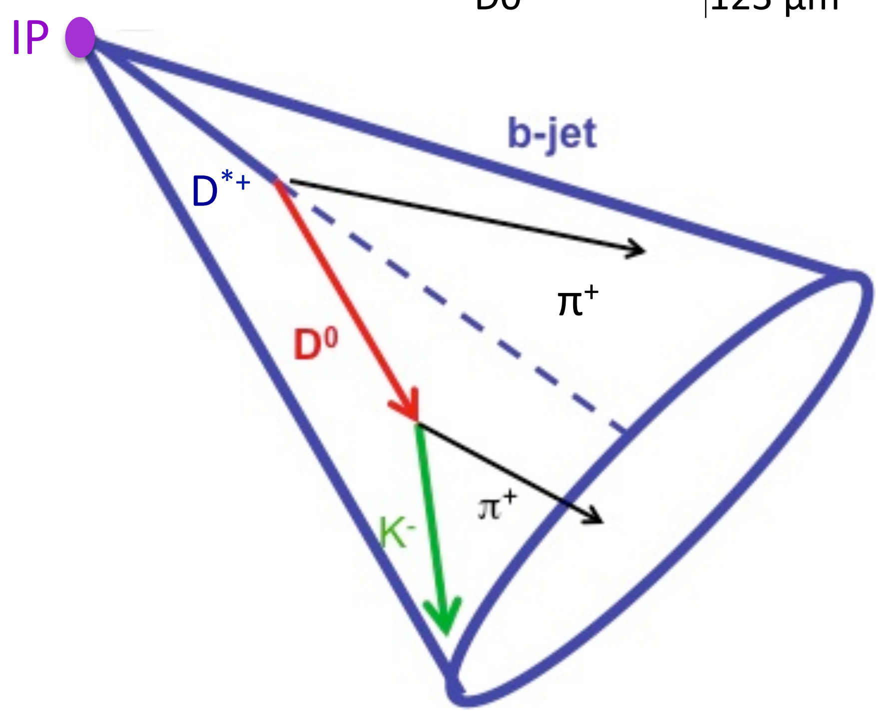
Particles from the struck parton -> Jet substructure

- Identification of secondary/tertiary vertices
- Particle identification
- High resolution tracking

- Fragmentation function/structure function

particle	cτ
π±	7.8 m
π0	25 nm
K±	3.7 m
K0S	2.7 cm
K0L	15.3 m
D±	312 μm
D0	123 μm



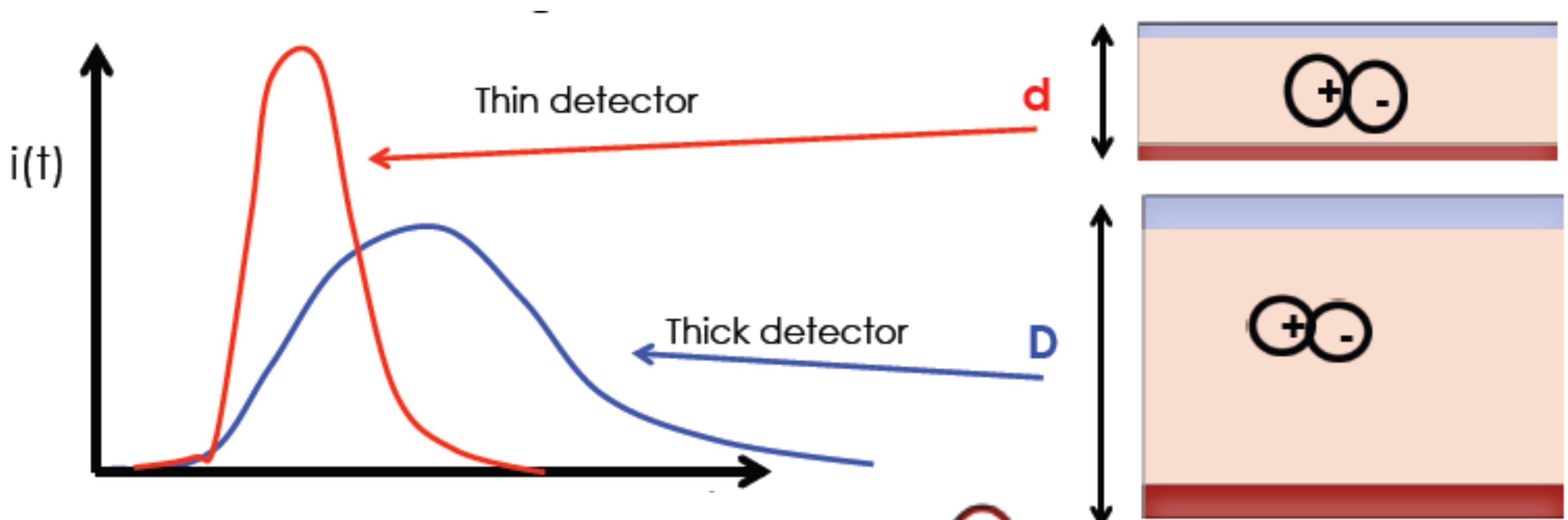


Ultra Fast Silicon Detectors

How do we achieve fast timing on the order of 10 ps?

- Current traditional silicon technologies have rise time ~1-10 ns determined by the drift velocity in an electric field

1) Faster speeds achieved by reducing the length e-h pairs travel -> Thin Sensors



$$\int [i_{el}(t)+i_h(t)]dt = q \qquad i \propto qv\frac{1}{d}$$

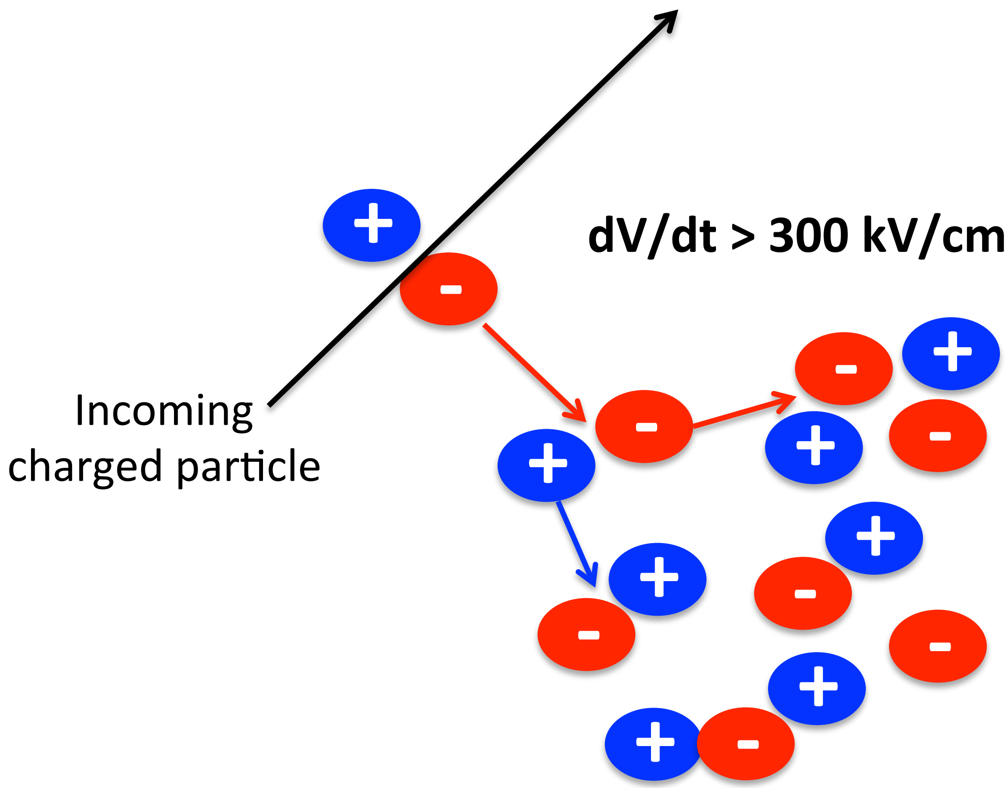
Current of one electron-hole pair

Nicolo Cartiglia CERN EP Detector Seminar 9/26/2014

Ultra Fast Silicon Detectors

How do we achieve fast timing on the order of 10 ps?

2) Create an avalanche region to achieve larger gains



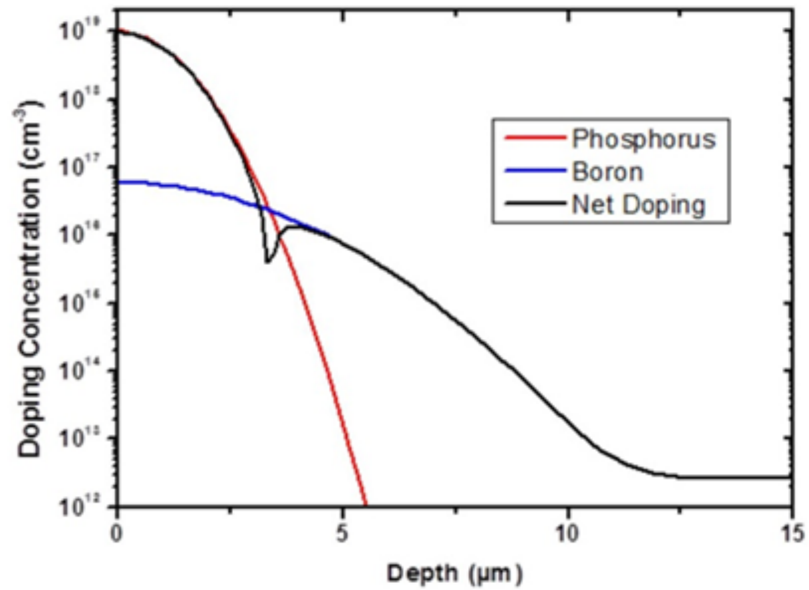
Create large potential gradient by applying a region of high doping concentration $N_D > 10^{16}$ /cm^3

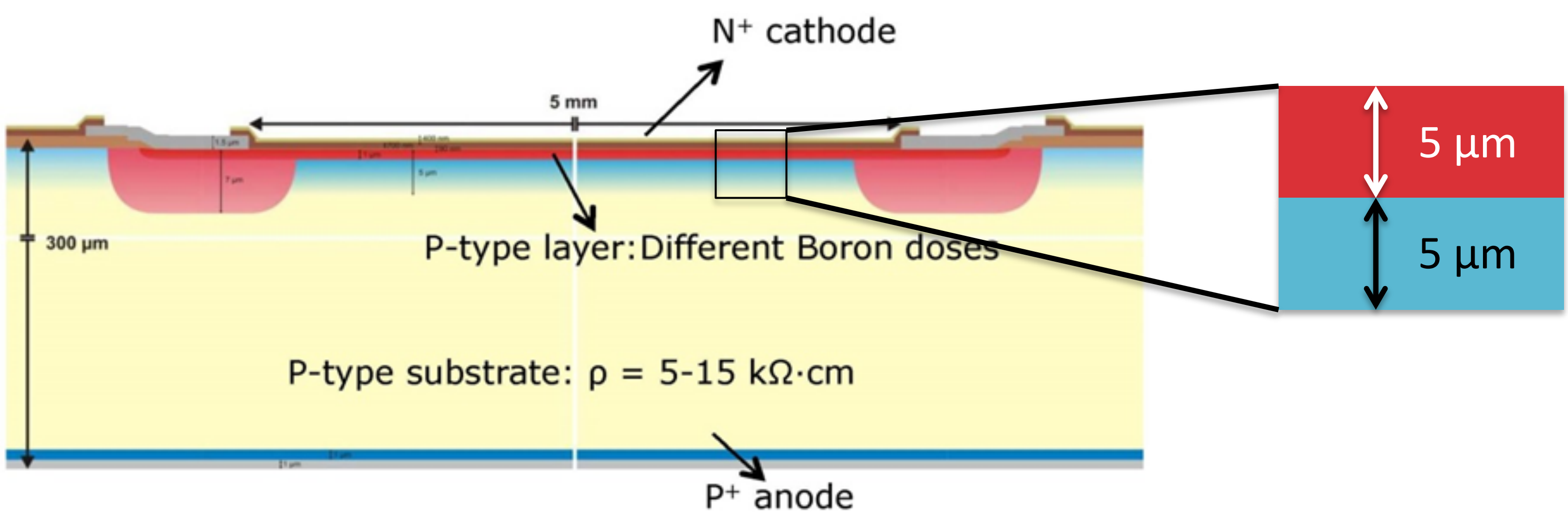
Gain factor ~ >10x more charge observed

Low Gain Amplifying Detectors (LGAD)

LGAD

- amplification region, ~5 µm thick
  - thin layer of Boron or Gallium
  - modifies the effective doping concentration profile -> electric field profile to create high field gradient
- Radiation tolerance shown up to 10^{14} n_{eq}/cm^2
  - not as tolerant as traditional silicon due to the high reactivity of the accelerant layer





Sadrozinski, CPAD Meeting, Arlington 2015

Fast Timing Silicon Detectors

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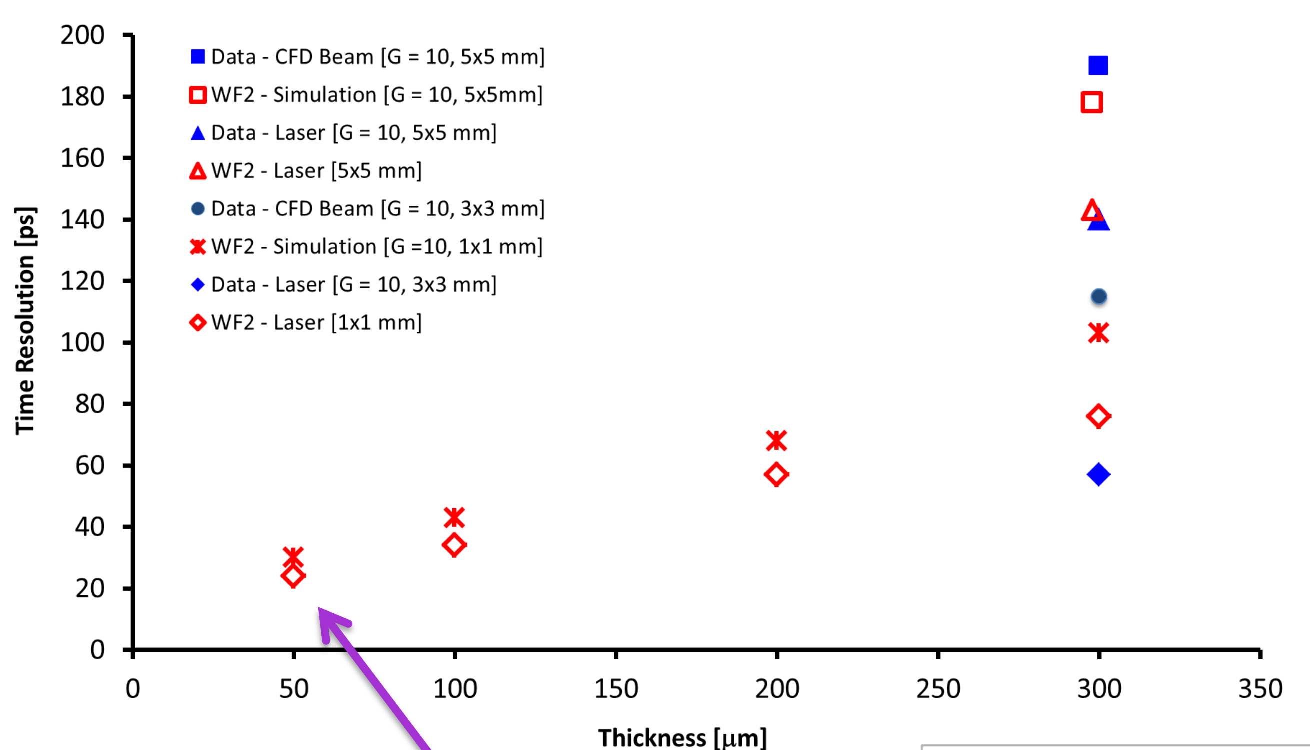
Silicon Detector R&D for EIC:



Sadrozinski, CPAD Meeting, Arlington 2015

Time resolution (in ideal lab conditions) approaching 10 ps

Fast Timing Silicon Detectors

Limiting Factors:

Shot Noise

- Main factor is the leakage current in the bulk
- Multiplication region also adds to the noise due to stochastic nature
- Signal enhancement from gain increases more slowly (G) than the noise increase ($\sqrt{G^{2+x}}$) due to the gain factor limiting the overall effectiveness of increasing the gain on the S/N ratio -> limits gain factor, $G < 20$

Non-uniform field profile

- Reduces the amount of peak charge collected
- Distorts collected signal based on where incident particle strikes

-> Thin, square geometry electrodes and high resistivity bulk for uniform electric field profile
-> High field for maximal drift velocity
-> low capacitance to minimize noise
-> small volumes to minimize leakage current and Shot noise

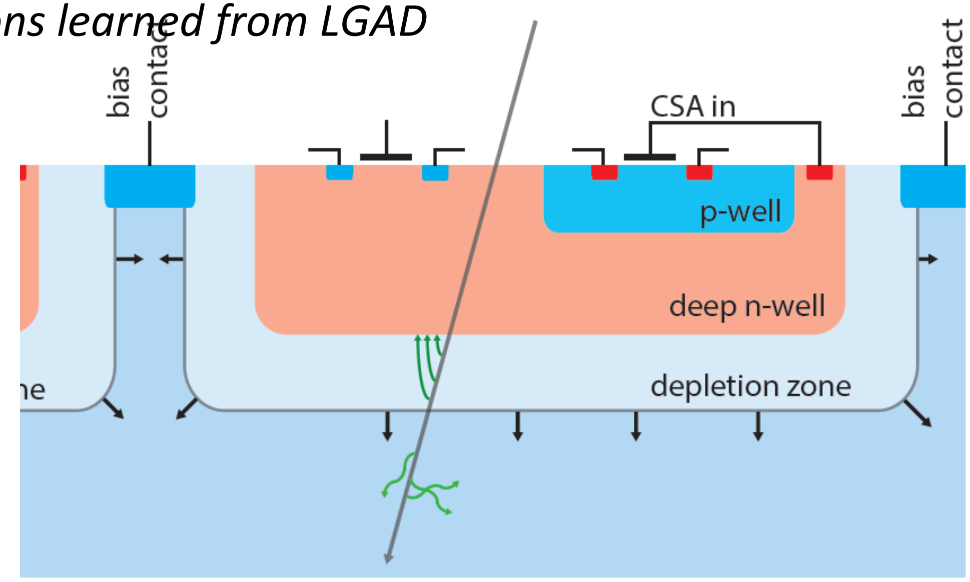
Answer: CMOS Monolithic Active Pixel Sensors (MAPS)

- Reduce effective capacitance -> noise
- Provide on-pixel amplification -> tolerate lower charge amplitude -> can go thinner

HVCMOS MAPS

HVCMOS MAPS
(high voltage complimentary metal oxide semiconductor monolithic active pixel sensor)

- Less expensive by x2 than traditional silicon sensors
  - Integrated sensor + signal amplification
  - Use commercially available CMOS processing with a few modifications
    - Deep n-well to isolate on-pixel electronics
    - high resistivity substrates for high voltage without breakdown
- Timing is currently ~1 ns
  - *Apply gain layer in HV CMOS to achieve 10 ps timing?* **-> never done before**
  - *investigate the possibility with simulations*
  - *Can use lessons learned from LGAD*



Fast Timing Silicon Detectors

4D Silicon Tracking Detector Design Targets

	Tracker	EM calorimeter	Best achieved
Pixel size	20-50 μm	1 cm	✔
Time resolution	**10 ps**	10-30 ps	50 ps
Radiation tolerance (N_{eq}/cm^2)	$1x10^{15}$ (?)	$1x10^{14}$	$1x10^{14}$
Monolithic design	yes	yes	no

- Target values to be confirmed with simulations included in this proposal

Fast Timing Silicon Detectors

Proposed Work: Year 1
Simulation intensive

1) Detector simulations

- Verify target requirements for timing, pixel size, radiation dose
- Investigate timing impacts on physics performance
  - Use the software framework for the SiD detector
  - Sergei Chekanov @ ANL is an expert and will supervise student/postdoc
    - Submitted separate proposal for (complimentary) simulation work

  - Benefits of timing
    - Vertex reconstruction
    - Track reconstruction
    - Particle ID
    - As an EM calorimeter
    - In a forward detector

Fast Timing Silicon Detectors

Proposed work: Year 1

2) Sensor Simulation

- Simulate the LGAD sensor using Sylvaco TCAD and/or WeightField2.0 (current software used for LGAD simulations)
  - Custom geometries
  - Specify different materials, non-uniformities
  - radiation effects
    - Response of an incident particle
      - Drift current generation
      - Diffusion current
    - Response to radiation damage
    - Electronics -> key to incorporate MAPS design
  - Expertise at Argonne in the APS division
    - Agreed to share knowledge and Sylvaco license

Fast Timing Silicon Detectors

Proposed work: Year 1

3) Sensor Design

- Identify challenges and methods to implement a MAPS design
    - Establish collaboration with a designer, TBD
    - Identify fabrication site that may be able to implement the parameters we need
        - CMOS process
        - High resistivity substrate
        - Doping for the gain layer

Fast Timing Silicon Detectors

Proposed work: Year 1

3) LGAD Sensor Testing

- Collaborate with UC Santa Cruz to learn to test their devices
  - Set up DAQ chain, most likely SAMPIX
  - Participate in test beams (travel funds)
  - Probe station measurements
    - IV, CV
  - Laser and/or radioactive source measurements to induce signal charge
  - Charge collection efficiency
  - Transient Current Technique for estimating the effective doping concentration
- Year 1 and 2: Establish procedures for microscopic analysis
  - Leverage experience in Material Science (and Nano Technology divisions)
    - Scanning laser microscopy
    - Spectroscopic techniques
    - Effective doping concentration, types of defects, trapping centers, resistivity, mobility, etc.

- Support to integrate LGAD to test stand and for MSD expertise is wrapped into the electrical engineer (EE) and mechanical engineer (ME) support at ~ 5 weeks each

Fast Timing Silicon Detectors

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Plan Summary:

		PI	postdoc	grad student	EE	ME	Sensor designer	TCAD expert	Simulation expert	Material expert
	Year 1									
Detector Simulation	evaluate the impact of 4D detector on physics performance using fast/full simulation	✔		✔					✔	
	define target timing resolution	✔		✔					✔	
4D Sensor Simulation	TCAD simulation of monolithic LGAD device	✔	✔					✔		
4D Sensor Design	design 4D sensor concept for target timing resolution (expected 10-30 ps)	✔	✔				✔	✔		
4D Sensor Testing	develop laboratory test stand	✔	✔	✔	✔	✔				✔
	gain experience with existing LGAD devices	✔	✔	✔						
	Year 2									
4D Sensor Design	implement design concept to target timing	✔	✔				✔			
4D Sensor Fabrication	join multi-project wafer run for production	✔	✔				✔			
4D Sensor Testing	laboratory test stand characterization measurements	✔		✔	✔	✔				✔
	Year 3									
4D Sensor Testing	irradiate and test 4D sensor samples	✔	✔	✔	✔	✔				
	perform test beam measurements with the 4D sensors	✔	✔	✔	✔	✔				
4D Benchmarks	assess potential of the technology to meet design targets for EIC	✔	✔	✔						
	define main technological challenges	✔	✔	✔						
	propose solutions	✔	✔	✔						
4D Sensor Design (Optional)	implement solutions in new design	✔	✔							

Fast Timing Silicon Detectors

Budget

- All items represent fully loaded cost

	Cost ($k): Year 1	Year 2	Year 3
postdoc (50%)	65	65	65
graduate student	20	20	20
electrical engineer	20	10	10
mechanical engineer	20	10	10
sensor design	10	50	
multi-project wafer run		50	
materials and supplies	20	10	20
travel	5	5	15
TOTAL	**160**	220	140

4D: Fast Timing Silicon Detectors

Summary:

- 4D detectors are a novel, but growing, area in silicon detectors
- Ambitious program to use fast timing silicon detectors in the EIC
- Now is the time to explore technological advances

- Proposal aims to determine whether Ultra Fast Silicon Detectors are worth investing in for the EIC
  - Clearly identify design targets
  - Establish the physics benefit from timing info
  - Simulate current LGAD sensors
  - Draw a roadmap toward Ultra Fast Silicon MAPS

Thank You

Timing for Vertexing

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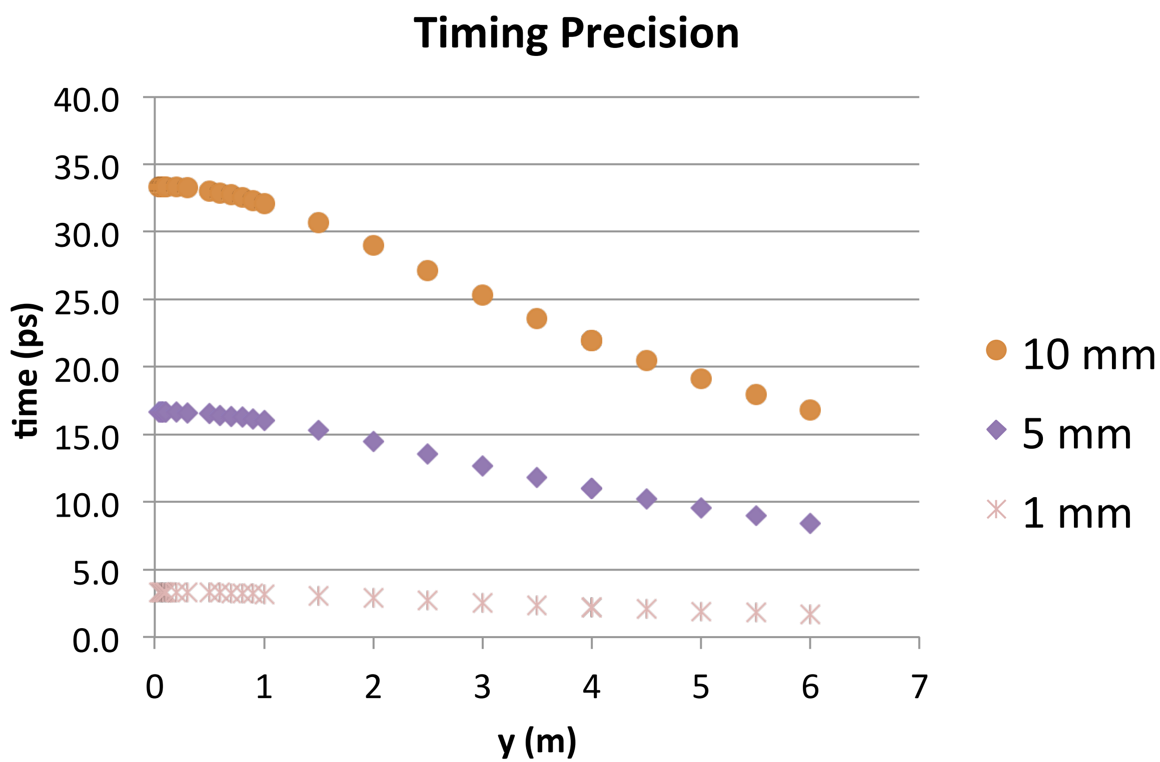
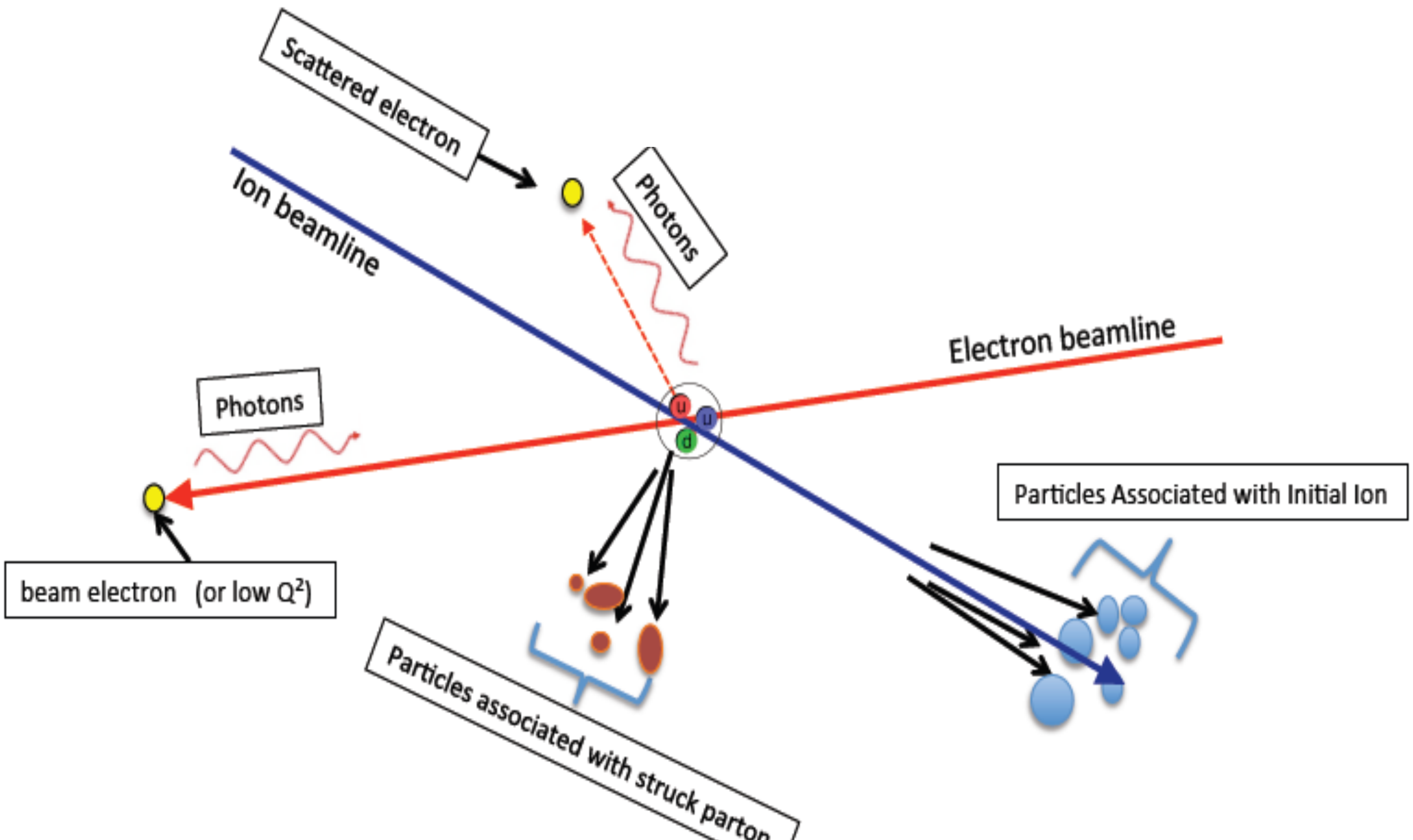
Timing precision

- Vertex identification in forward regions with timing is possible
  - Time of flight to detector to identify vertex
- Example for a detector at 3.5 m in z from IP



=> Timing on the order of 10 ps for particle ID, vertexing, and tracking

4D Silicon

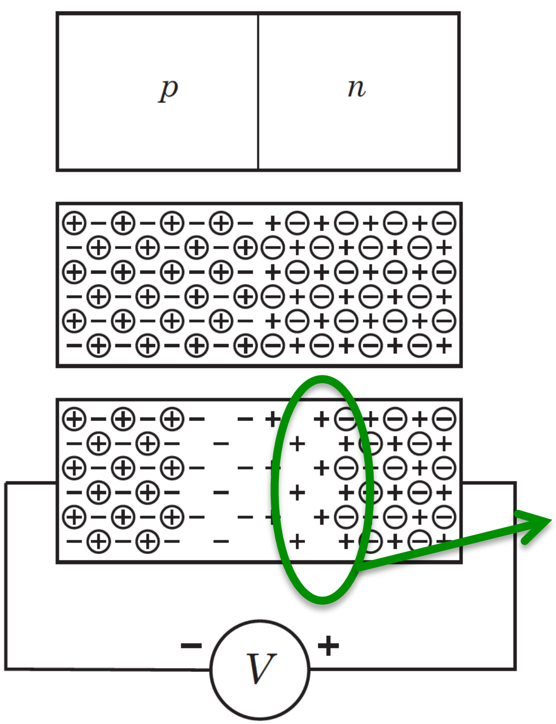


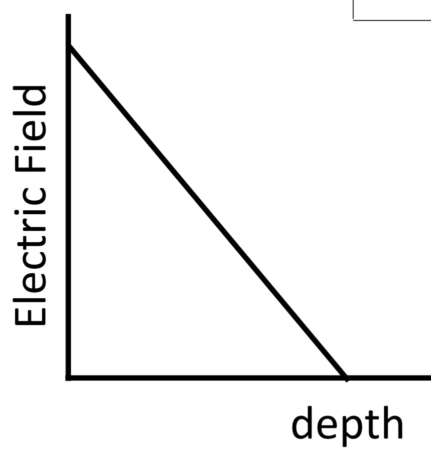
From Rik Yoshida's talk yesterday

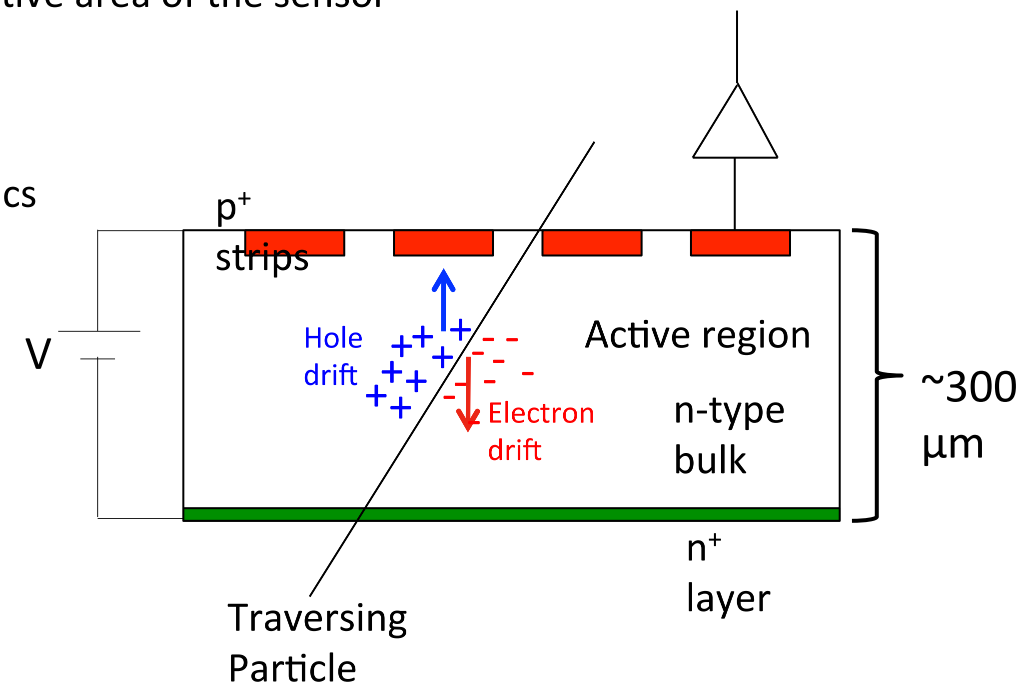
4D Silicon

Reminder of Silicon Detector Operation:

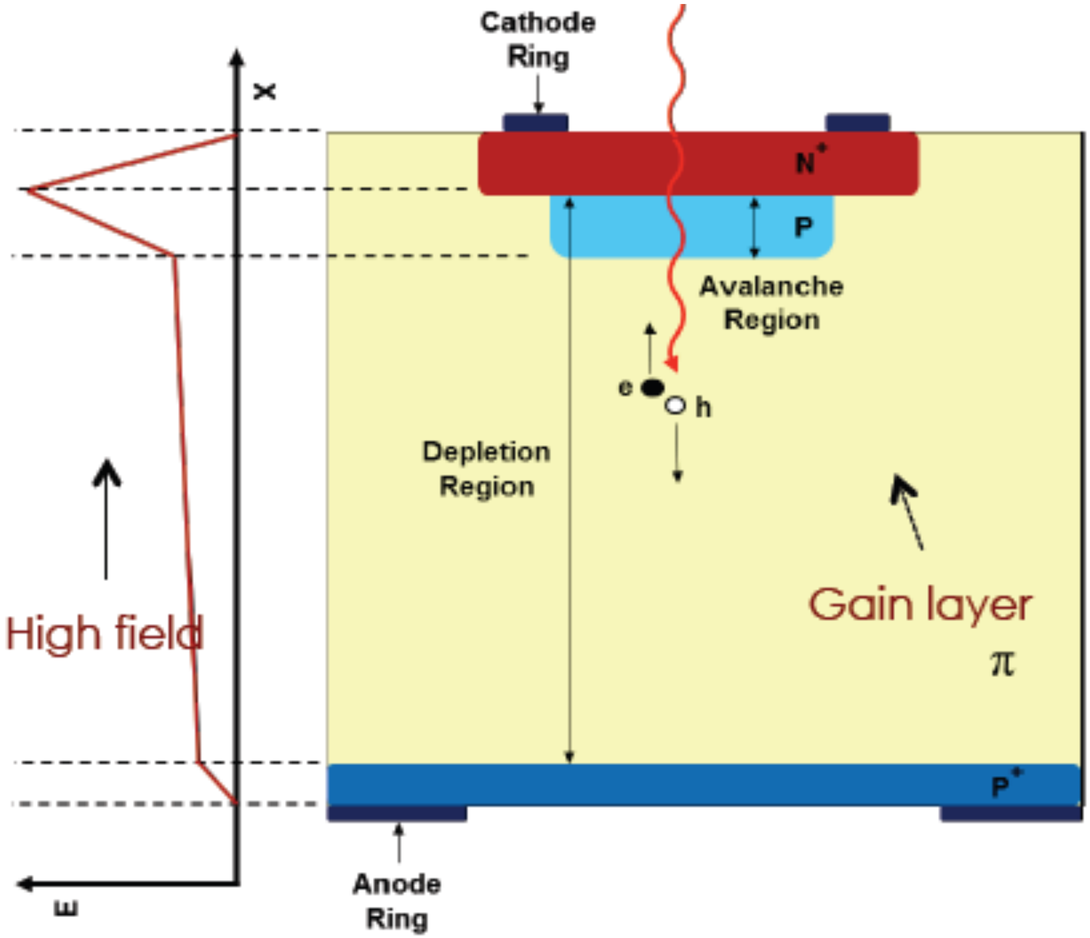
- Diode with p-n junction
- Apply bias voltage to create a region of stable space charge and linear electric field
  - this region is the depletion region or active area of the sensor
- MIP particle creates electron hole pairs
  - drift to strip implants and backplane
  - signal is read out by Front-End electronics







4D Silicon



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4D Silicon

How do we achieve fast timing on the order of 10 ps?

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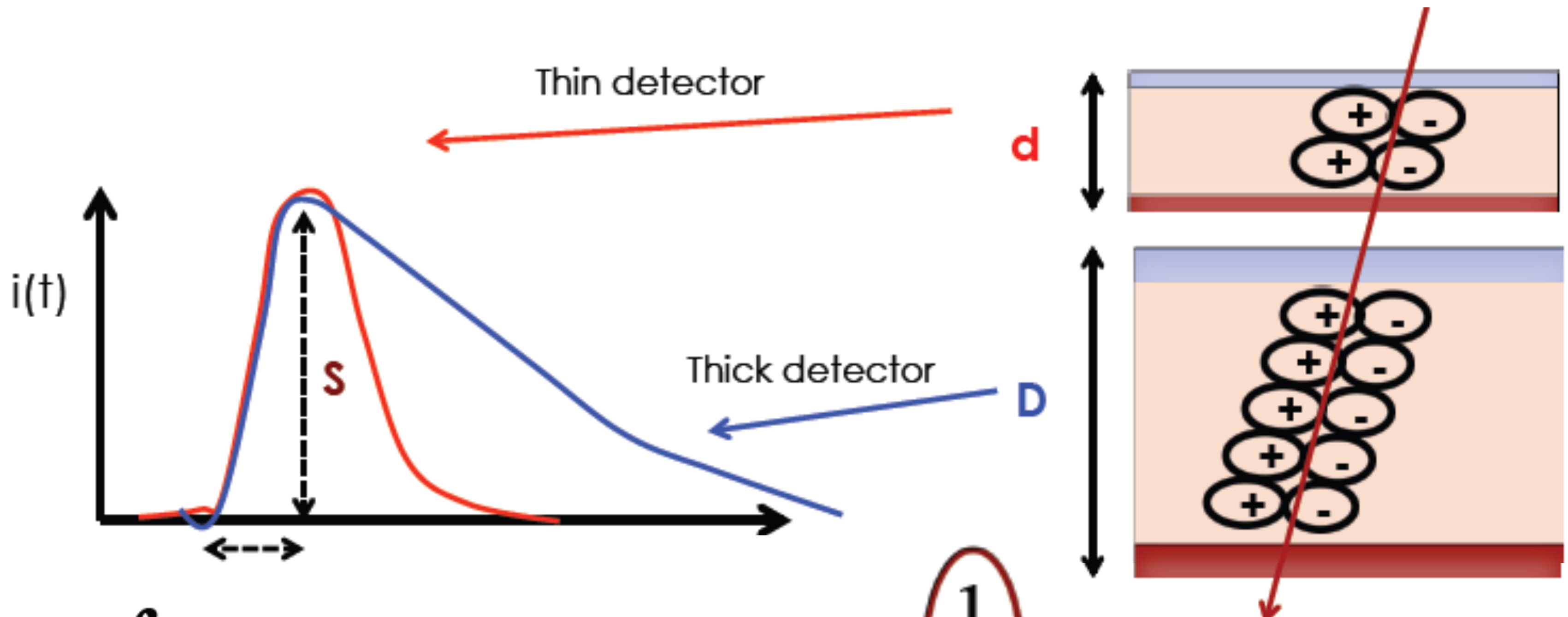
- Create an avalanche region



$$\int [i_{el}(t)+i_h(t)]dt = q \qquad i \propto qv\frac{1}{d}$$

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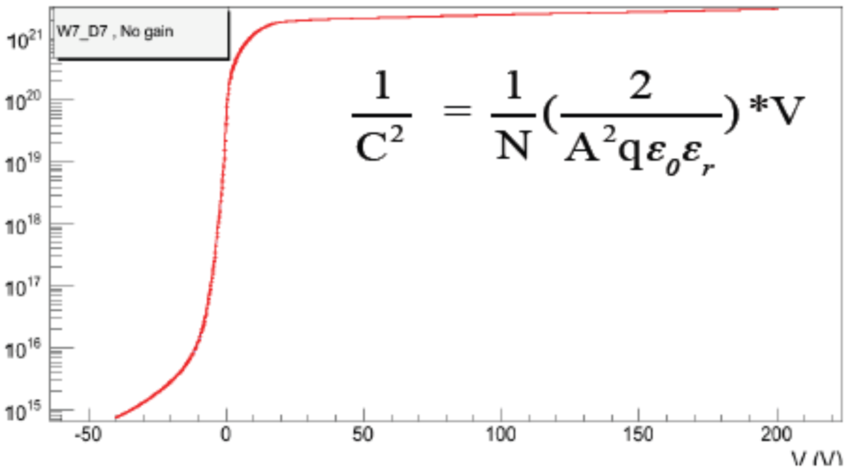
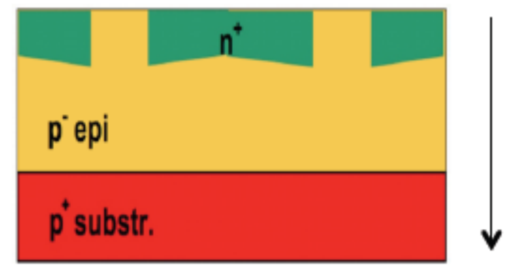
Doping profile from CV measurement - I

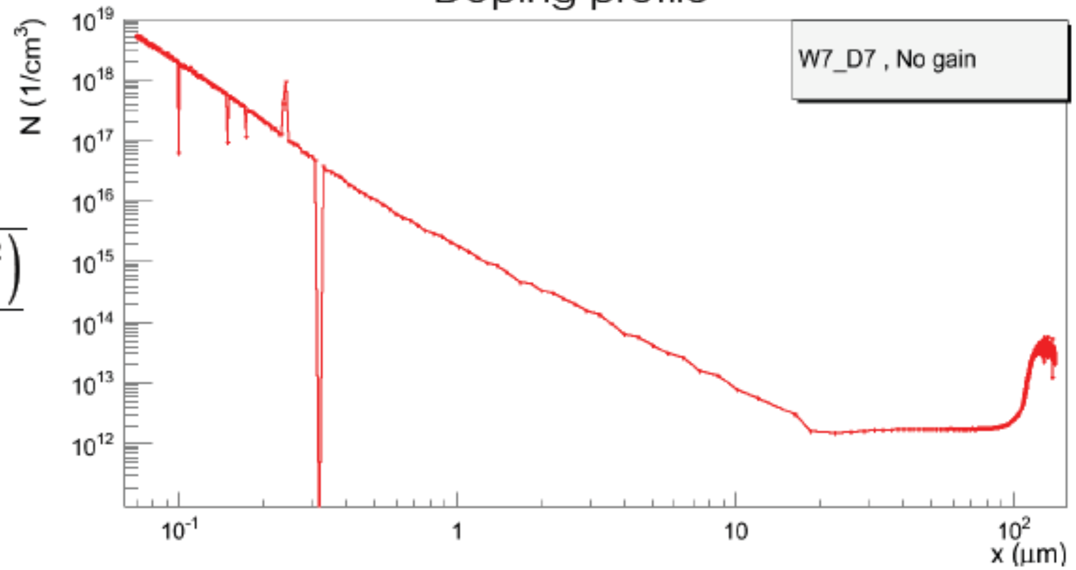


$$\frac{1}{C^2} = \frac{1}{N}\left(\frac{2}{A^2 q \varepsilon_0 \varepsilon_r}\right) * V$$

No-gain sensor



Doping profile



$$N = \frac{2}{q \varepsilon_0 \varepsilon_r A^2 \frac{d\left(1/C^2\right)}{dV}}$$

Doping

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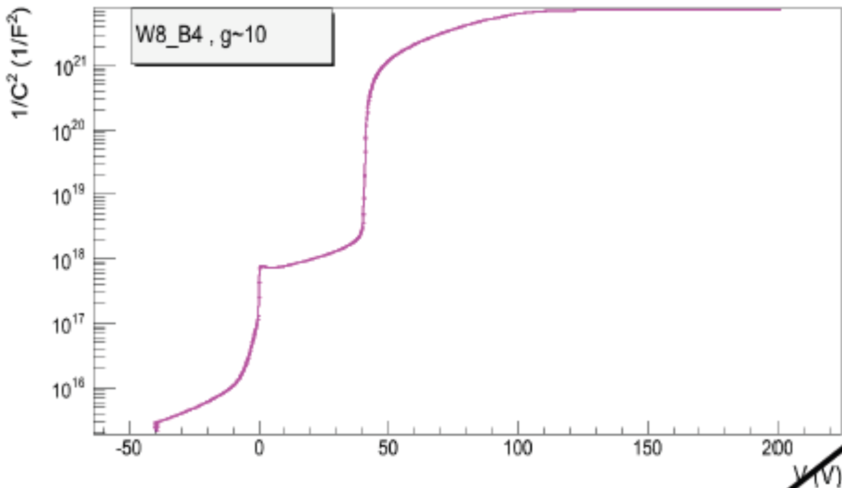
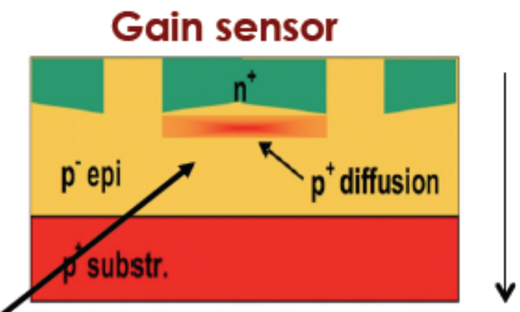
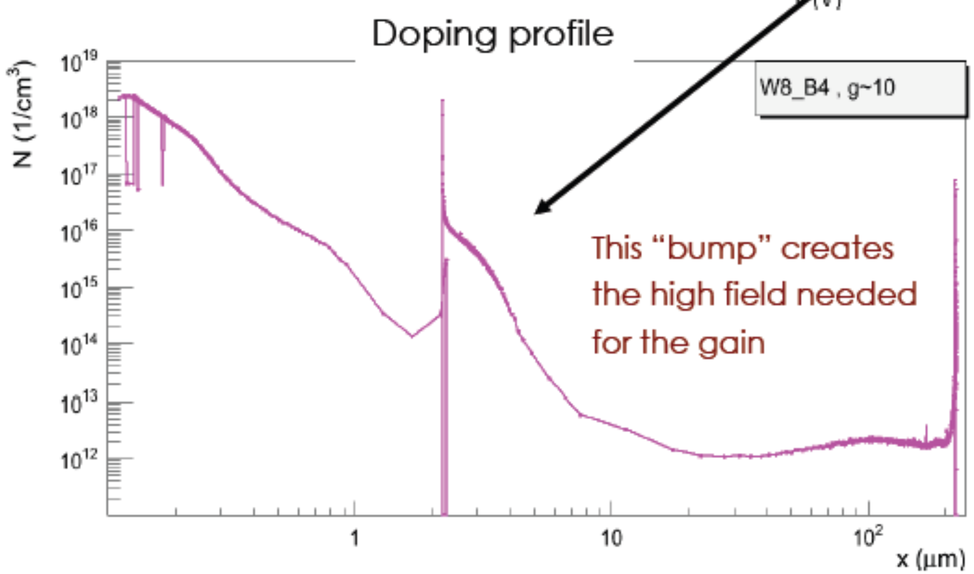
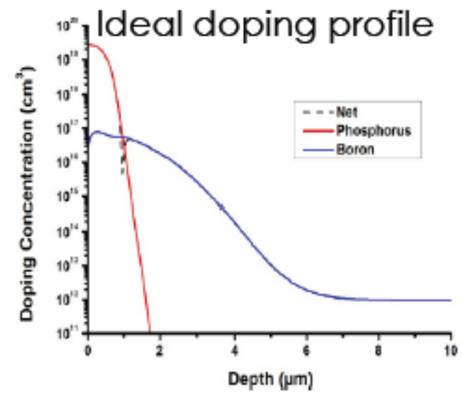
Doping profile from CV measurement - II







This "bump" creates the high field needed for the gain



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MSD: Scanning Laser Microscopy

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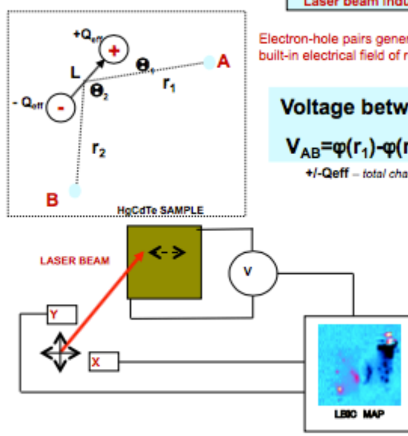
SPATIALLY RESOLVED CHARACTERIZATION OF HgCdTe MATERIALS AND DEVICES BY SCANNING LASER MICROSCOPY

-Non-destructive testing at various stages of device processing.
-Distribution and identification of electrically active defects (inclusions, strain, damage, twin bound., bandgap and doping variations, dislocation clusters, precipitates , stacking faults)

Laser beam induced current (LBIC) mode

Electron-hole pairs generated at the point of illumination are separated by the built-in electrical field of regions in the vicinity of the incident light.

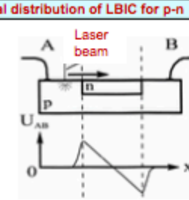


Voltage between points A and B

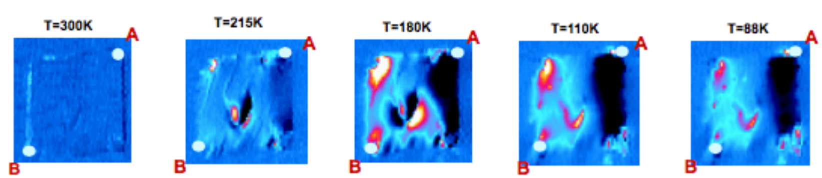
$$V_{AB}=\varphi(r_1)-\varphi(r_2)=Q_{eff}L/2\pi\varepsilon\varepsilon_0(\cos\Theta_1/r_1-\cos\Theta_2/r_2)$$

+/-Qeff – total charges of separated electron-hole pairs

Spatial distribution of LBIC for p-n junction



TEMPERATURE DEPENDANCE OF LBIC for MCT epitaxial film



Different electrically active areas of the film can be found with temperature LBIC measurements

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